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OPTICAL INSTRUMENTATION STUDIES IN AEROSPACE FACILITIES--A PROJECT SUMMARY

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ARO, Inc.

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VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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ARO, Inc.

FOREWORD

The work reported herein was done at the request of Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65802F.

The results of research presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee under Contract F40600-73-C-0004. The research was conducted between July 1971 and June 1972 under ARO Project No. VW5232, and the manuscript was submitted for publication on July 7, 1972.

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This technical report has been reviewed and is approved.

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ABSTRACT

Evaluations and remedial modifications to laser photography systems have resulted in a 30-percent increase in reliability for optimum performance. Another unique modification to the laser photographic technique has added the capability for flow visualization when desired. A 70-percent increase in spatial resolution has resulted from refinements to photopyrometry systems. Evaluations have shown that temperature measurement accuracies on the order of ±2 percent (±80°K at a measured temperature of 4000°K) may be achieved with the improved systems. Investigations of schlieren-related flow visualization techniques resulted in the selection of a focused shadowgraph arrangement for detection of boundary-layer transition on conical models. Preliminary designs for photographic instrumentation systems for use during erosion testing have been completed.

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SECTION I
INTRODUCTION

Laser photographic systems, photopyrometry systems, flow visualization systems, and other optical instrumentation have been developed and have demonstrated effectiveness in obtaining useful data from models in hypervelocity flight within the aeroballistic ranges of the von Kármán Gas Dynamics Facility. To maintain performances near state-of-the-art levels, an experimental research program involving system evaluations and improvements was initiated. As part of this program, certain evaluations and modifications of optical measurement systems were conducted under ARO Research Project VW5232. The purpose of this report is to present the results of this project.

SECTION II
EVALUATIONS AND MODIFICATION OF LASER PHOTOGRAPHIC SYSTEMS

Certain aerophysical studies in aeroballistic ranges require accurate inflight measurements of the contours of hypervelocity models. The nature of the required measurements suggested a direct-photography approach to the instrumentation problem, and inherent characteristics of the pulsed, ruby laser made it an obvious candidate as the light source in such a photographic system. It was reasoned that the laser's short time duration (~20 nanoseconds) should effectively "stop" model motion at speeds up to 20, 000 fps; that the high light intensity (~75 megawatts of peak power or ~1. 5 joules of energy) should provide adequate film exposure; and that the monochromaticity of the laser light should allow filtering of unwanted light such as might arise from luminous model ablation processes.

Photographic systems employing pulsed, ruby lasers as light sources were thus adapted for use in aeroballistic ranges and have proved very successful in fulfilling this instrumentation need. These systems and results of their applications are described in detail in Refs. 1 through 4. At present, eight laser photography systems are employed in the 1000-ft Hyperballistic Range (G). Locations and descriptive characteristics of these systems are given in Table I (Appendix II). A photograph of one such installation in the Range G is shown in Fig. 1 (Appendix I). One laser photography system is available in the 100-ft Hyperballistic Range K. A laser for this system is shared with one of the Range G systems. The characteristics of the Range K system are noted in Table I.

Laser photography systems provide high-quality, stop-motion photographs which permit observation of minute surface details and allow detailed contour measurements of test models in hypervelocity free flight. Figure 2 is a laser photograph of a model in flight at 11,400 ft/sec within Range G. A smoke trail from one of the protuberances, called spoilers, is clearly in evidence. The slight nose-up attitude of the model caused aerodynamic heating and consequent burning of the spoiler.

2.1 FOCUS IMPROVEMENT

Range G laser photographic systems employ as many as 24 camera lenses (four lenses per 4- by 5-in. camera body) at some range locations. (Table I) to provide at least one well-focused photograph of a model in flight past each station. A schematic diagram of one of these systems, as generally used at downrange locations, is shown in Fig. 3. A detailed description of this front-light/back-light arrangement is given in Ref. 4. The large number of camera lenses is necessary because of the shot-to-shot dispersion of flight path. It is imperative that the location of best focus for each lens be known and remain fixed from shot to shot so that there are no gaps in the overall viewfields.

Inconsistencies of focus were noted for many camera lenses during initial operation. This problem was traced to a slight buckling of the films in film holders. A technique was devised and implemented whereby the film in each camera could be held firmly and consistently in place by application of a pressure differential across the film. An array of small holes was drilled through the back of each 4- by 5-in. film cassette. A "vacuum" as provided by an ordinary household vacuum cleaner was applied to the back side of the cassette, holding the film uniformly against the cassette surface. Cameras of all Range G laser photographic systems were converted to the inexpensive vacuum-back arrangement; Tygon® tubing was employed to connect as many as six camera cassettes to a single vacuum cleaner. The vacuum attachments can be seen in the photograph of Fig. 1.

2.2 VIEWFIELD MAPPING

After solution of the film flatness problem with vacuum cassettes it was necessary to refocus many of the cameras. This refocusing was done, and the viewfield of each system was "mapped" to ensure that there were no viewfield locations through which a model might pass without appearing in sharp focus in one of the resulting photographs.

The desired viewfield of a Range G laser photographic system is a three-dimensional region. Two dimensions of this viewfield, the vertical dimension and the dimension along the model flight path, are fixed by the viewing angle of the cameras in combination with the size of the illuminated spot on the background card (see Fig. 3). The third dimension of the viewfield, depth, is, of course, the most difficult to achieve and to ascertain the extent thereof. Since each particular camera lens has a finite depth of field*, nominally 4 in., the problem involved in establishing the required total depth of field became one of arrangement of the depths of field of many individual lenses in such a manner that the desired total depth was covered by the group. The approach to the problem of establishing and mapping the depth dimension of the viewfield of the Range G systems is described below.

First, the lenses of each camera were adjusted in the laboratory to predetermined center-focus positions. Then, the lenses and cameras were installed in the range, and the preset lens focuses were checked by viewing (with the aid of a 10X eye-piece) a resolution chart at various positions inside the range using incandescent chart lighting. Any big discrepancies in the preselected focusing designs were then corrected by adjusting focus of individual lenses and re-examining the incandescently lighted resolution chart.

A static evaluation technique was devised for mapping the depths of field. The experimental arrangement used is shown in Fig. 4. A resolution chart, calibrated in lines per inch, served as the standard for determining camera lens resolution. The chart was mounted on an optical bench, as shown in Fig. 4, to facilitate precise identification of the resolution chart's location. Design of the optical bench was such as to allow movement of the resolution chart in known increments along the optical axis of any camera in the system.

It was known that camera focus would differ slightly for the monochromatic laser light case from that of the incandescent light case; therefore, actual photography of the resolution chart, using the laser source, was employed for final focus of all lenses. The arrangement shown in Fig. 4 was used to photograph the resolution chart with a par-

*The depth of field (theoretically, a function of focal length, aperture, and object distance) as used herein is defined as that distance in object space over which an object could be photographed with a resolution of at least 125 lines per inch. Depth of field, according to this definition, was found to be a function of lens quality and construction, and hence was found to vary somewhat from lens to lens.

ticular camera lens at 1-in. increments along the optical axis of that lens. The resulting photographs were examined, and fine focus adjustments were made, as required, to each lens. This sequence of adjustment, photography at incremental positions, and examination was then repeated until the desired focus was achieved for each lens of the particular camera. This obviously tedious process was then repeated for each of the other cameras in the system. Fortunately, once focused, the lenses of each system can be locked into place so that any desired focus configuration can be maintained indefinitely. A typical viewfield map, established in the manner described above, of one of the more complex front-light/back-light systems (Fig. 3 and Table I) is shown in Fig. 5. Each of the viewfield areas shown in Fig. 5 represents the total depth of field for one particular camera (four lenses). It can be seen from this map that at least one well-focused photograph of a test model, either front lighted or back lighted, can be obtained if the model flies anywhere within approximately ±18 in. (vertically or horizontally) of the optimum flight path (centerline of the range).

Viewfield maps were completed for the eight laser photographic systems presently used in Range G. Since installation of the vacuum cassettes and subsequent mapping of viewfields, a near 100-percent reliability has been realized in regard to obtaining a sharply focused photograph of a model passing through the viewfield of any one of the laser photography systems. This compares with a reliability of about 70 percent prior to these modifications.

2.3 A NEW DIMENSION IN FRONT-LIGHT LASER PHOTOGRAPHY

A technique was devised which adds a new dimension to laser photography -- the capability for flow visualization. Normally, an opaque white screen is used as a background in the front-light laser photography systems, and little or no usable flow detail is visible in the resulting front-light photograph (see Fig. 6).* The all-white background in one of the two-camera, front-light systems (Fig. 7) was replaced by a striped screen which subsequently was used during several shots in the VKF aeroballistic ranges. Typical photographic results are shown in Fig. 8. The refractive properties of flow-field density gradients displace features in the out-of-focus image of the high-contrast, bar-chart background in such a manner that some flow characteristics are visible.

*A crude depiction of the bow shock wave appears in the out-of-focus shadow on the background card.

Deflections of light rays by density gradients are shown by Holder and North (Ref. 5) to be proportional to the first derivative of aerodynamic density with distance. The displacements in images of the bar chart that result from such deflections are therefore related to density in the same manner.

The photographs of Fig. 8 contain the same high-quality surface detail as those with a uniform white background (cf. Figs. 6 and 8). The flow visualization capability can then be added without sacrifice of surface detail resolution, by a simple change to a high-contrast background.

While this flow visualization technique does not possess the sensitivity usually associated with conventional schieren and shadowgraph methods, there are instances wherein certain aerodynamic features are elucidated better by its use. In particular, under cerain high-velocity/high-pressure conditions, the luminosity of the shock cap and model surface can be quite deleterious to ordinary schlieren and shadowgraph depiction of flow detail in the stagnation region. In addition, true model appearances in classical shadowgrams are very often distorted by the strong density gradients of the shock cap, sometimes to the extent that there is little or no distinction between the model surface and the bow shock. The laser photography technique does not experience the harmful effects of either self luminosity or strong density gradients. Optical filters are used to remove the unwanted shock-cap radiation, allowing only the laser light (and that small portion of the shock cap radiation at the laser wavelength) to reach the film. Distortions from looking at the model through the enveloping flow field are minimized in the laser photography technique since cameras are focused precisely on the plane of the model. Cameras are focused on the shadow of the model in the classical shadowgraph techniques.

Quantitative measurements of the shock detachment distance were made from the photographs of Fig. 8; these results are tabulated below along with theoretical predictions from Ref. 6 for comparison.

Velocity, ft/sec	Range Pressure, atm	Nose Radius, in.	Shock Detachment Distance, in.	
			Measured	Theoretical (Ref. 6)
12,650	1	0.750	0.0708	0.0675
3,660	1	1.00	0.197	0.193

These results are in agreement with theory to within 5 percent for the higher velocity case and within 2 percent for the lower velocity case. Past experience has shown that for conditions similar to those for the high-velocity case (12, 650 ft/sec), shock detachment measurements from schlieren photographs or shadowgrams are dubious, to say the least.

The preliminary results from this novel flow visualization technique are encouraging. To the author's knowledge, this technique is unique in that both flow characteristics and front-lighted surface detail are recorded in a single photograph. It has been demonstrated that this method is practically immune to the effects of self-luminosity and strong density gradients which often hamper flow visualization with other, more sensitive systems under conditions of the sort for which results are shown here. Utilization of the new dimension of laser photography should enhance the capability of aeroballistic ranges for conducting certain tests.

2.4 OBLIQUE-VIEW ARRANGEMENT

Studies in the 100-ft Hyperballistic Range (K) employing temperature-sensitive paint on the nosetips of test models required oblique views as well as the normal broadside views of these models in flight. To achieve the oblique view, a third camera was added to the Range K laser photography system (originally as pictured in Fig. 7). This camera was mounted slightly downrange from the original station and a mirror was used to provide a viewing angle of 40 deg from head-on as shown in Fig. 9. The original arrangement of side-on illumination and side-view cameras (Fig. 7) was not changed; thus, the complete system (see Note, Table I) provided the desired broadside and oblique views simultaneously.

Figure 10 shows a typical result obtained with the oblique camera; Fig. 8b is the broadside view obtained simultaneously from the Range K system. The paint (watermelon-like stripes) is clearly visible in both these photographs. It is anticipated that photographs such as these will allow experimenters to interpret temperature data from the characteristics of the special paints used.

SECTION III
MODIFICATIONS AND EVALUATIONS OF PHOTOPYROMETRY SYSTEMS

The surface temperatures of aerodynamic models in free flight within aeroballistic ranges are of particular interest to investigators in the field of reentry physics. Several stringent requirements are imposed upon a pyrometric instrumentation system for these transitory measurements of surface temperatures. Among these are: (1) a measurement duration of 100 nanoseconds or less, (2) a measurement of, typically, 2500 to 4000 deg K, (3) a highly reliable calibration technique, (4) a field of view and depth of field compatible with normal flight-path dispersion, and (5) spatial resolution on the order of 0.02 in. A photographic pryometry method (Refs. 7 through 14) was chosen because this technique appeared to offer both the spatial (and temporal) resolution necessary for making the desired surface temperature measurements and is applicable to the aeroballistic range by using conventional high-speed photography techniques.

Photographic pyrometry systems have been developed within the VKF and have demonstrated the capability for measurements of temperatures on the surfaces of models in flight at velocities as high as 18,000 ft/sec in the 1000-ft Hyperballistic Range G. A schematic representation of such a Range G photopyrometer is shown in Fig. 11. Three such systems are presently used in Range G and are described in detail in Ref. 15. Locations and characteristics of these systems are given in Table II.

Surface temperature data are obtained by photographing the self-luminous model surfaces with a high-speed, image converter camera which usually views the model at an oblique angle, facilitating the desired nosetip inspection. The film densities (gray levels) of the image converter photographs (black-and-white negatives) provide a measure of temperatures of incandescent model surfaces through use of predetermined film density vs temperature calibrations. Calibrations are performed by use of the carbon arc shown in Fig. 11.

Temperatures measured by the method described above are, of course, brightness temperatures. True temperatures may be calculated if the emissivity of the model material is known. In many instances, model nose materials are carbon and graphite compounds with emissivities very near unity. In these cases, temperatures measured are representative of true temperatures (to within the measurement accuracy of the photopyrometry systems).

3.1 RESOLUTION IMPROVEMENTS

Objective lens arrangements that provide optimum resolution under the restraints imposed by field-of-view and depth-of-field requirements were designed for the three Range G photopyrometry systems. Implementation of these lens arrangements resulted in a considerable improvement over the lens systems which were used during early development of the photopyrometry technique. For example, object-plane resolutions associated with the early systems were on the order of 50 mils; whereas, object dimensions as small as 15 mils can be resolved with the improved systems (see Table II).

The photopyrometry systems employ commercially avilable image converter cameras having image converter tubes of the proximity-focused type (Ref. 15). External optics must be supplied to image the region of interest onto the front face (photocathode) of the tube. Schematic diagrams of image converter camera systems (relay-lens coupled and fiber-optics coupled) and optical arrangements used in Range G photopyrometry systems are shown in Fig. 12. Pertinent characteristics and resulting resolutions of these systems are given in Table II.

3.2 ACCURACY STUDIES

Knowledge of the accuracy of surface temperature measurements made with the photopyrometry systems is obviously essential. System repeatability, reliability of calibration, data reduction integrity, and other factors directly related to measurement accuracy were critically evaluated during initial development of the photopyrometry technique (Ref. 15). A direct analysis of the overall system accuracy was recently completed via experimental static measurements of known temperature values.

A carbon arc lamp of known temperature (3806 ± 10°K) was placed inside the aeroballistic range and within the viewfield (Fig. 11) of the photopyrometry system. This lamp is traceable to an NBS calibration through a secondary standard maintained at the AEDC. Photographs were made of the carbon arc lamp in this position; these photographic data were reduced, treating the carbon arc as an unknown temperature source. System calibration was performed in the usual manner (Ref. 15) with a carbon arc lamp outside the range as shown in Fig. 11. Ten experimental measurements of the temperature of the carbon arc lamp were made with each Range G photopyrometry system. All these measurements were found to be within ±2 percent (±80°K) of the known value of 3806 ± 10°K of the lamp.

It is felt that this assessment of accuracy, while made under static conditions, is indicative of the system accuracy which is realized during dynamic measurements of the brightness temperatures of aeroballistic range test models. The slight motion blur during range measurements should have insignificant effect on temperature measurements since this blur is considerably less than the optical resolution capability of the photographic systems, as can be seen from Table II.

3.3 INVESTIGATION OF COLOR DATA FORMAT

A Spatial Data Systems 703 densitometer which converts film densities (shades of gray) in a black-and-white image to a spectrum of colors is available within the VKF. It was hoped that this machine, which displays a color-coded density map of an image of interest on a color television screen, could be utilized for expedient extraction of surface temperature contours from photographs made with the Range G photopyrometry systems.* An investigation disclosed several peculiarities which make it difficult to obtain a meaningful density calibration of the color densitometer; for example, the color-coded density map cannot be converted reliably to a temperature map via the carbon-arc calibration data. As a result, uncertainties on the order of ±150°K were found to be introduced by the machine. It was concluded that, because of this degree of uncertainty, the color densitometer is undesirable for routine handling of Range G surface temperature data. It was found, however, that the machine is quite useful when relative temperature measurements are of interest or when quick-look, first-approximation data are desirable.

SECTION IV
INSTRUMENTATION FOR DETECTION OF BOUNDARY-LAYER TRANSITION ON CONE MODELS

Users and potential users have shown an interest in studies of the flow characteristics (in particular, transition from laminar to turbulent flow) within the boundary layers of high-speed cone models. Flow visualization techniques routinely used in the VKF aeroballistic ranges,

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*Normally, a scanning microdensitometer is employed which digitizes and records density information on magnetic tape; computer processing yields the desired isothermal contours. This data reduction technique, described in detail in Ref. 15, is somewhat time consuming.

i. e., knife-edge schlieren and Fresnel-lens (refocused) shadowgraphs, lack the sensitivity to record such minuscular events. Dark-field schlieren and focused shadowgraph techniques were investigated experimentally in Ranges G and K in search of a means by which the desired characteristics might be observed.

4.1 DARK-FIELD SCHLIEREN

The Range K schlieren system was converted to the dark-field arrangement shown in Fig. 13. This arrangement differs from the more conventional knife-edge schlieren arrangement only in that a small-diameter wire is used at the focal point of the second schlieren mirror (M_2, Fig. 13) instead of a knife edge.* Several Range K shots were monitored with the dark-field arrangement and experimenters were unable to distinguish the flow regions of interest. A typical result is shown in Fig. 14a. (Figure 14b, a focused shadowgraph result, will be discussed later). Very little boundary-layer detail is evident in this dark-field photograph.

The dark-field arrangement was shown, however, to provide useful flow visualization at higher velocity conditions in Range G. The Range G schlieren system was converted to dark-field and used during several shots. Figure 15 is an example from a 17,200 ft/sec launch. The depiction of wake characteristics and geometry is especially good. This particular flow visualization system, while not applicable for boundary-layer studies, may be of interest in the future for observation of less subtle flow characteristics.

4.2 DIRECT FOCUSED SHADOWGRAPH

After the unsatisfactory results (from the standpoint of observing boundary-layer transition) with the dark-field arrangement, the Range K schlieren system was converted to another of its operational configurations, the direct focused shadowgraph arrangement. This arrangement is the same as that shown in Fig. 13 except that there is no wire or other obstruction in the focal plane of the second mirror, M_2. The object in the case of the focused shadowgraph is to record an image of the spatial distribution of illumination in the plane on which the camera is focused, as discussed in Ref. 5. A plane of focus 12 in. to the camera side of range centerline was found to produce the best flow-field depictions.

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*The various operational configurations for schlieren systems of the type used in the VKF aeroballistic ranges are discussed in Ref. 5.

Figure 14b is an example of a focused shadowgraph picture obtained during a cone launch in Range K. Flow characteristics within the boundary layer can be seen with more detail in this photograph than is the case in the dark-field schlieren photograph obtained under similar flight conditions (Fig. 14a). Experimenters are able to discern regions of transition from laminar to turbulent flow, as exemplified in Fig. 14b, from such photographs. The focused shadowgraph arrangement was used with quite satisfactory results during Range K boundary-layer transition tests.

SECTION V
INSTRUMENTATION FOR EROSION STUDIES

Special instrumentation systems will be required for use during future aeroballistic range erosion tests to study the effects of hypervelocity flight through erosive environments such as snow, rain, or ice fields. Preliminary designs were completed for stereo and multiview laser photographic systems for use in Range G during these future tests. Installation and evaluation of these instrumentation systems are beyond the scope of this project and are expected to be accomplished under FY 73 research projects.

5.1 STEREO LASER PHOTOGRAPHY SYSTEM

A photographic system was designed that will allow stereo viewing of the nose tip of a model in flight within Range G. Such systems will be required for measurements of crater depths on model noses after flights through the erosive environments. The preliminary design is shown in Fig. 16. This arrangement essentially employs two front-light laser photography systems (Fig. 7). Mirrors are used to provide oblique (45 deg from head-on) illumination and viewing of the model nose tip. Stereo pairs of lenses are used so that depth measurements may be made from resulting pairs of photographs through application of conventional stereo reduction techniques. A stereo pair consists of two identical lenses, with optical axes parallel, which are focused on the same object plane. Since each stereo pair has a relatively small depth of field, the focal planes of several stereo pairs of lenses are staggered to cover the desired total depth of field.

5.2 MULTIVIEW LASER PHOTOGRAPHY SYSTEM

A multiview laser photography system was designed to facilitate viewing of the model surfaces during erosion testing. This system, shown schematically in Fig. 17, will allow simultaneous viewing of the front, back, top, and bottom sides of a model in flight. Conventional front-light systems in Range G (Fig. 7) may be converted to the multiview configuration of Fig. 17 by addition of the vee-shaped, front-surface mirror. Focusing of camera lenses must be arranged to provide a depth of field which will encompass the virtual images produced by the mirror. These virtual images may be thought of as real objects in relation to the cameras.

SECTION VI
CONCLUDING REMARKS

The usefulness of laser photography systems and photographic pyrometry systems for aeroballistic range measurements has been enhanced significantly by the modification and refinements of the systems described herein.

Installation of vacuum cassettes and subsequent viewfield mappings resulted in a 30-percent increase in reliability for obtaining highest-quality data with the laser photography systems. Development of the striped background laser photography technique has added a new dimension to laser photography, the capability for flow visualization. Oblique-view laser photography systems have facilitated viewing in cases where the nose tips of models are of particular interest.

Improvements in the optical components for photographic pyrometry systems resulted in resolution increases (decreases in the smallest resolvable model dimension) of as much as 70 percent. The static accuracy of the improved photopyrometry systems was found to be ± 2 percent. Accuracy was not determined prior to the improvements. An available color-format microdensitometer was found to be unsuitable for routine handling of photopyrometry data but acceptable for quick-look data when desired.

Investigations of schlieren-related flow visualization schemes revealed that the focused shadowgraph technique is applicable for determination of boundary-layer transitions on conical models under some conditions. The dark-field schlieren technique as used here was deemed unsuitable for boundary-layer observation but was found to provide very good depictions of wake structure.

Preliminary designs for stereo and multiview laser photography systems were completed and subsequent work on such systems is expected to be accomplished under FY 73 research projects.

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APPENDIXES
I. ILLUSTRATIONS
II. TABLES

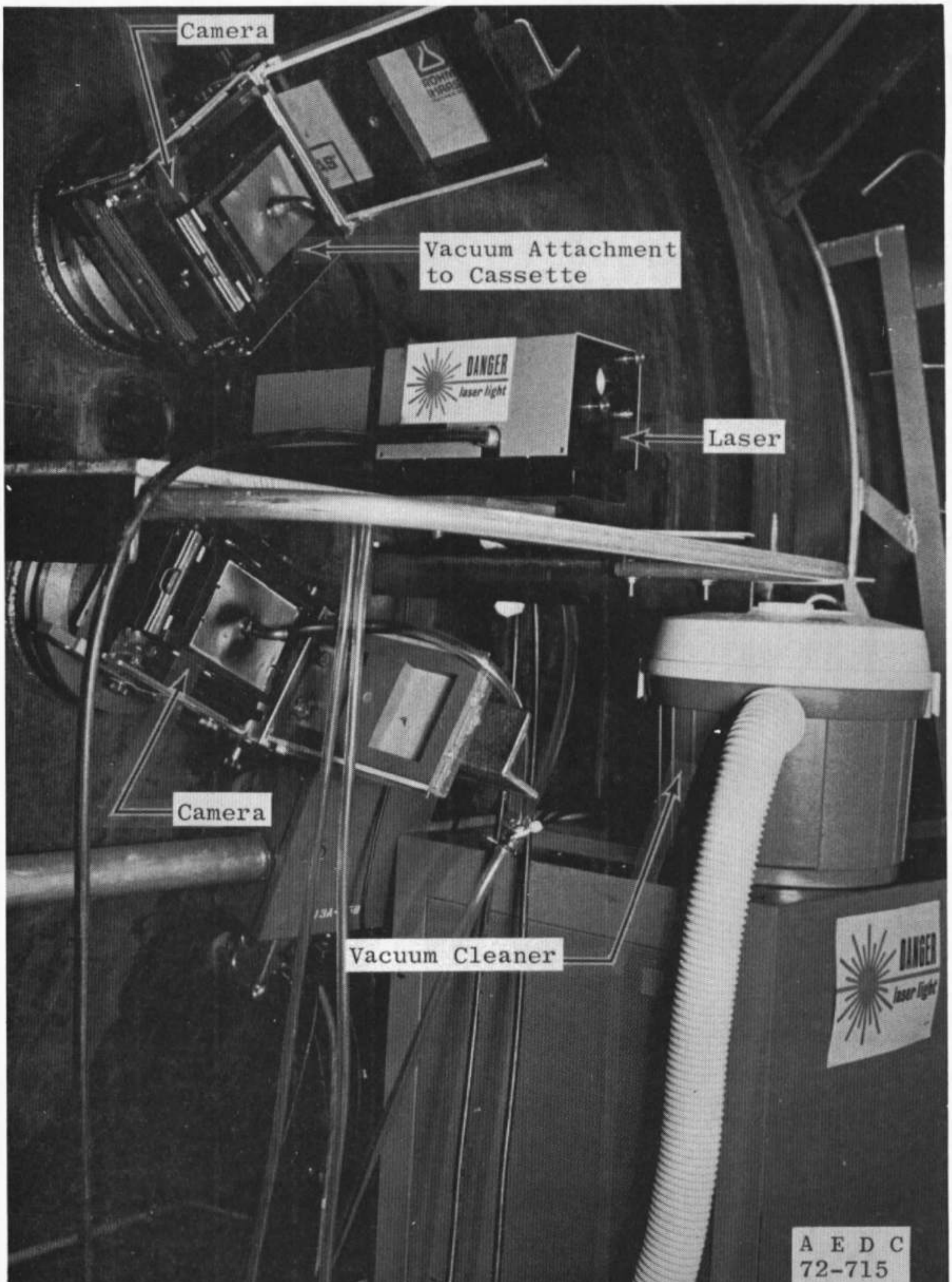


Fig. 1 Photograph of Front-Light/Back-Light Laser Photography Station in Hyperballistic Range G

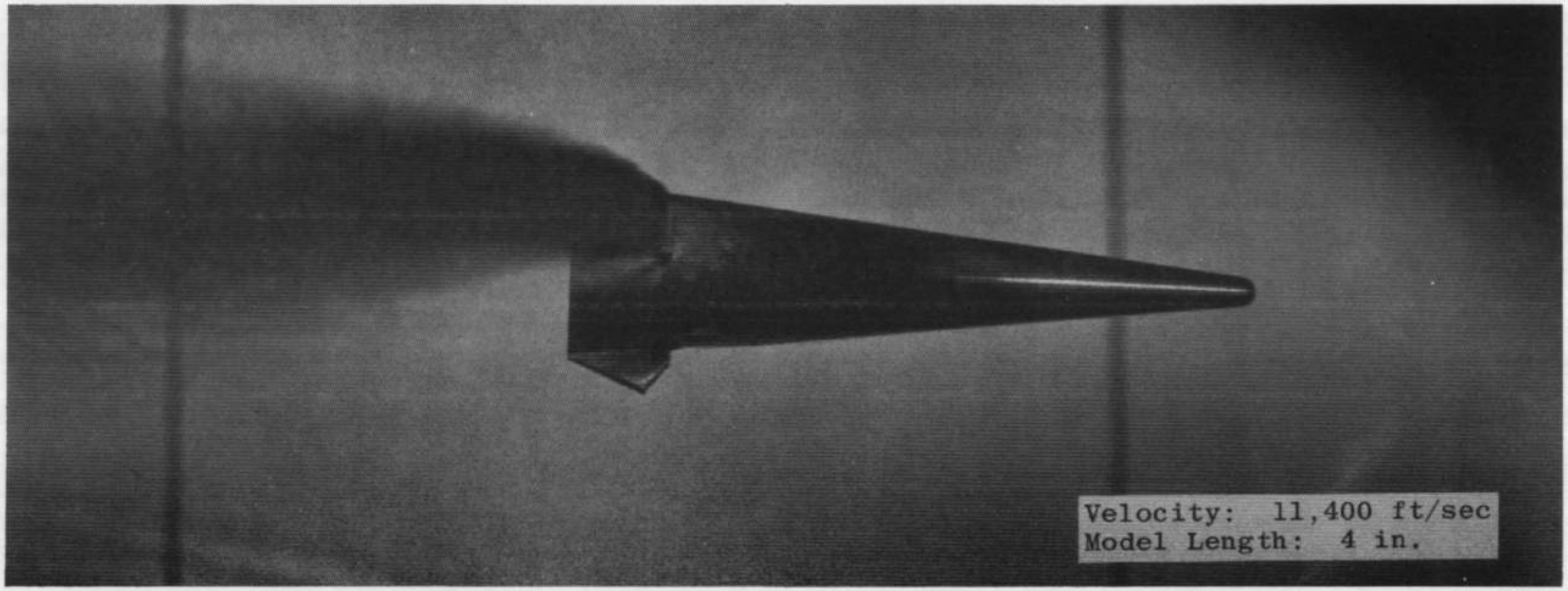


Fig. 2 Front-Light Laser Photograph

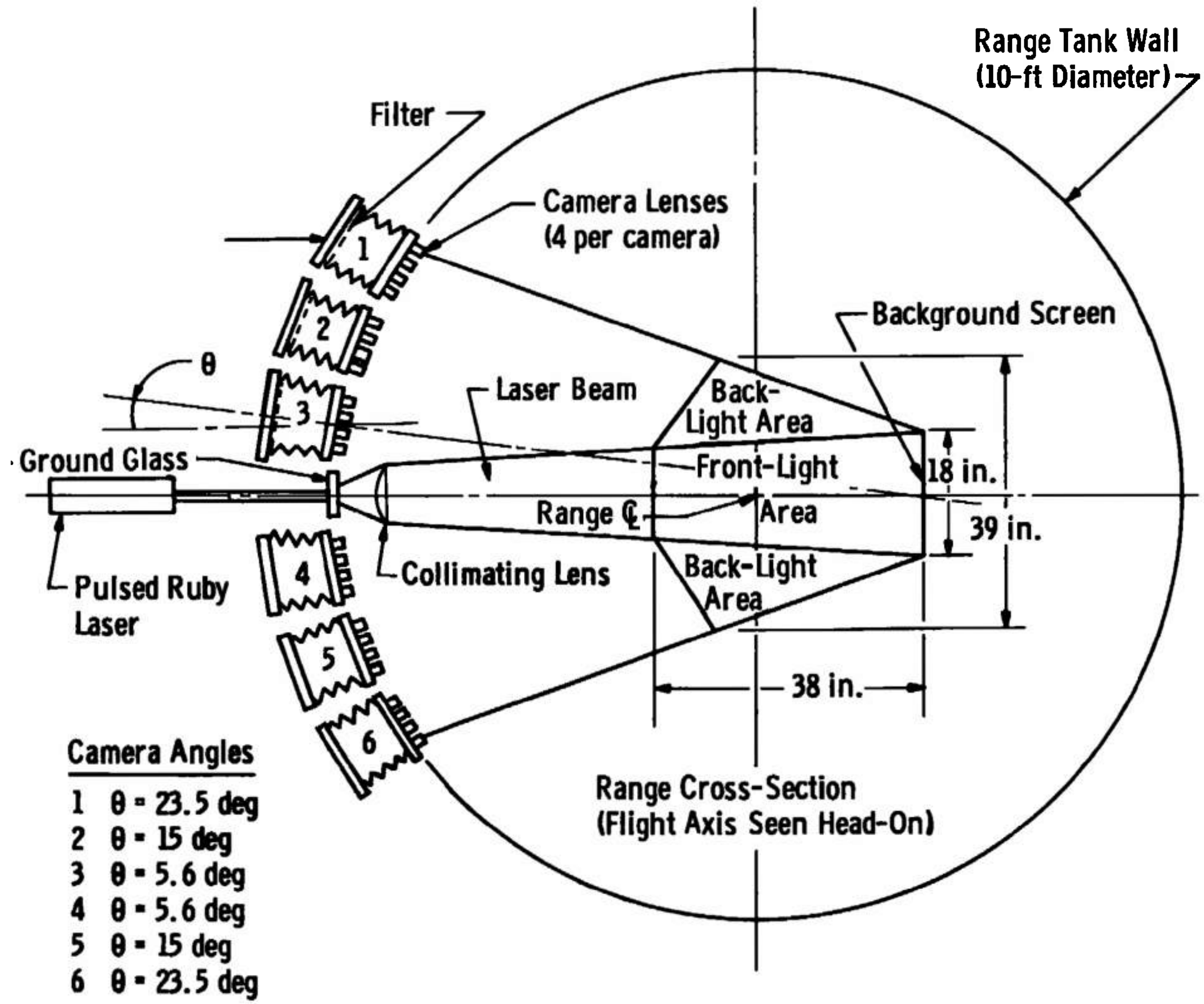


Fig. 3 Front-Light/Back-Light Laser Photographic System in Range G

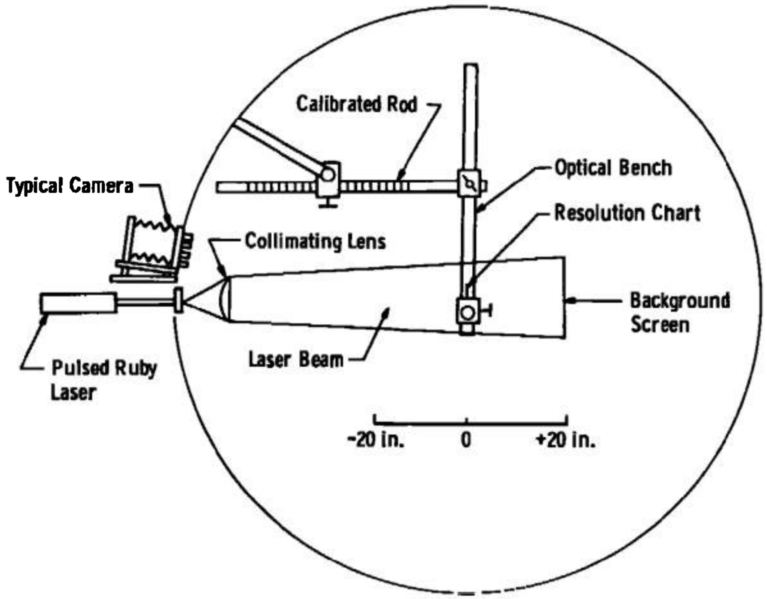


Fig. 4 Experimental Arrangement for Static Viewfield Mapping

Notes:

1. Camera numbers refer to designations in Fig. 1.
2. Any point within a designated area is in focus (measured resolution of 125 lines per in. or better) on at least one of the lenses associated with that camera.
3. Models inside the laser beam and within the mapped camera areas are photographed via the front-light mode; models outside the laser beam but within the mapped camera areas are photographed via the back-light mode.
4. The mapped areas differ from camera to camera because of the different viewing angles and depths-of-field associated with individual camera lenses.

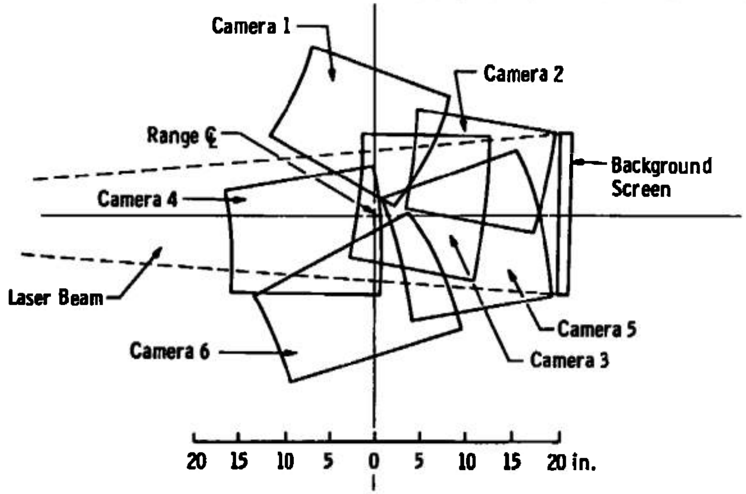


Fig. 5 Camera Map of Range G Front-Light/ Back-Light Laser Photographic System

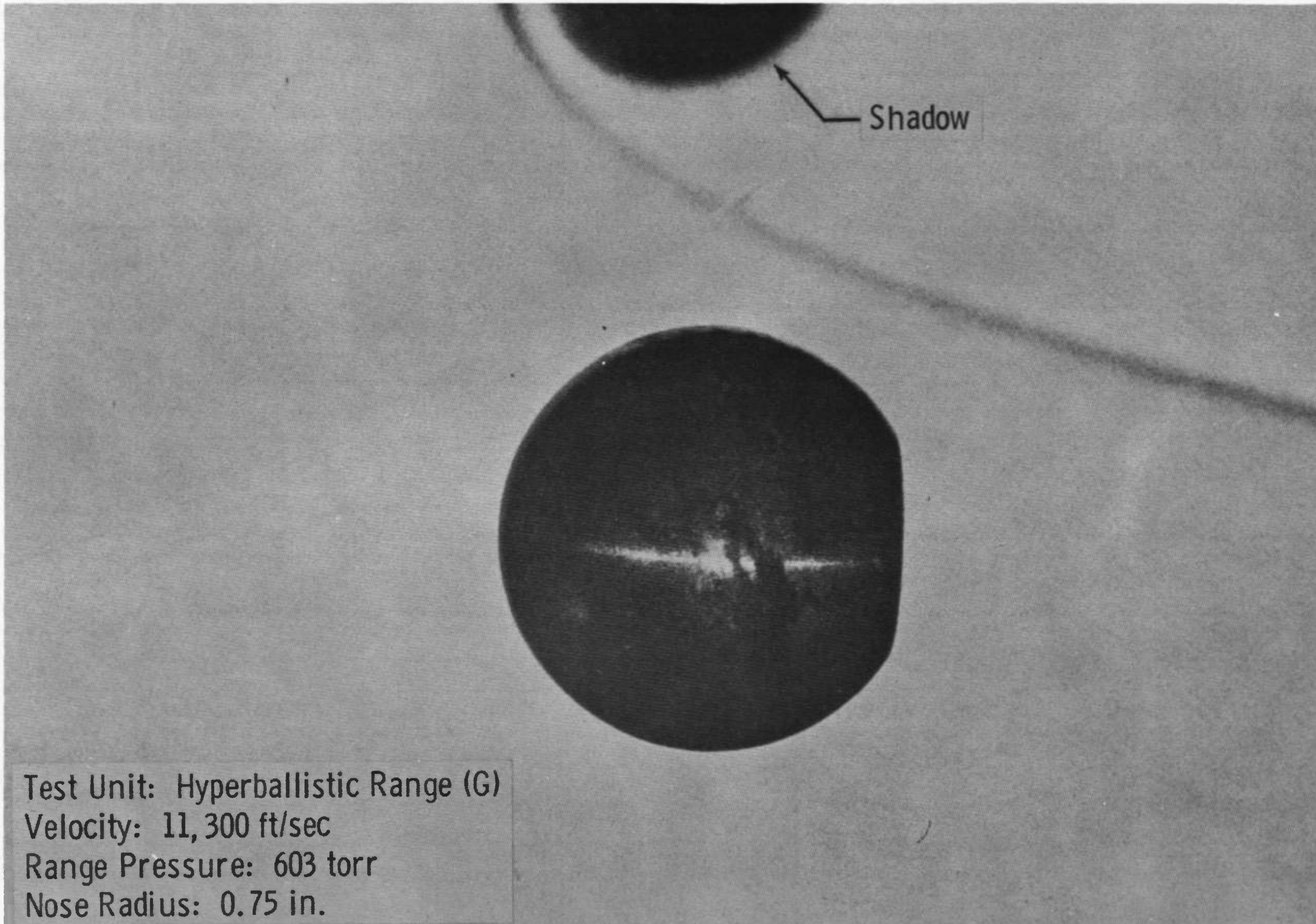


Fig. 6 Front-Light Laser Photograph—White Background

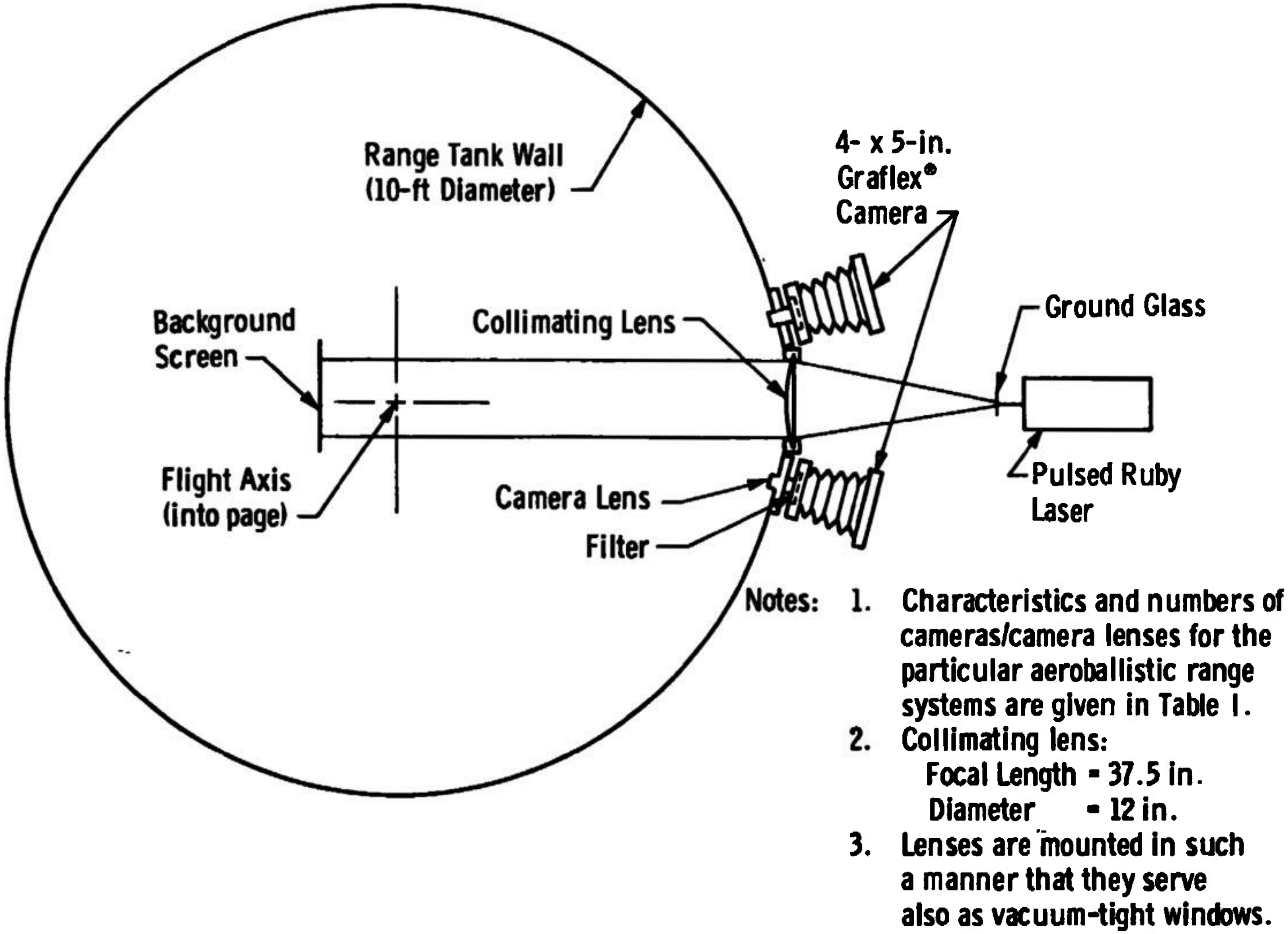
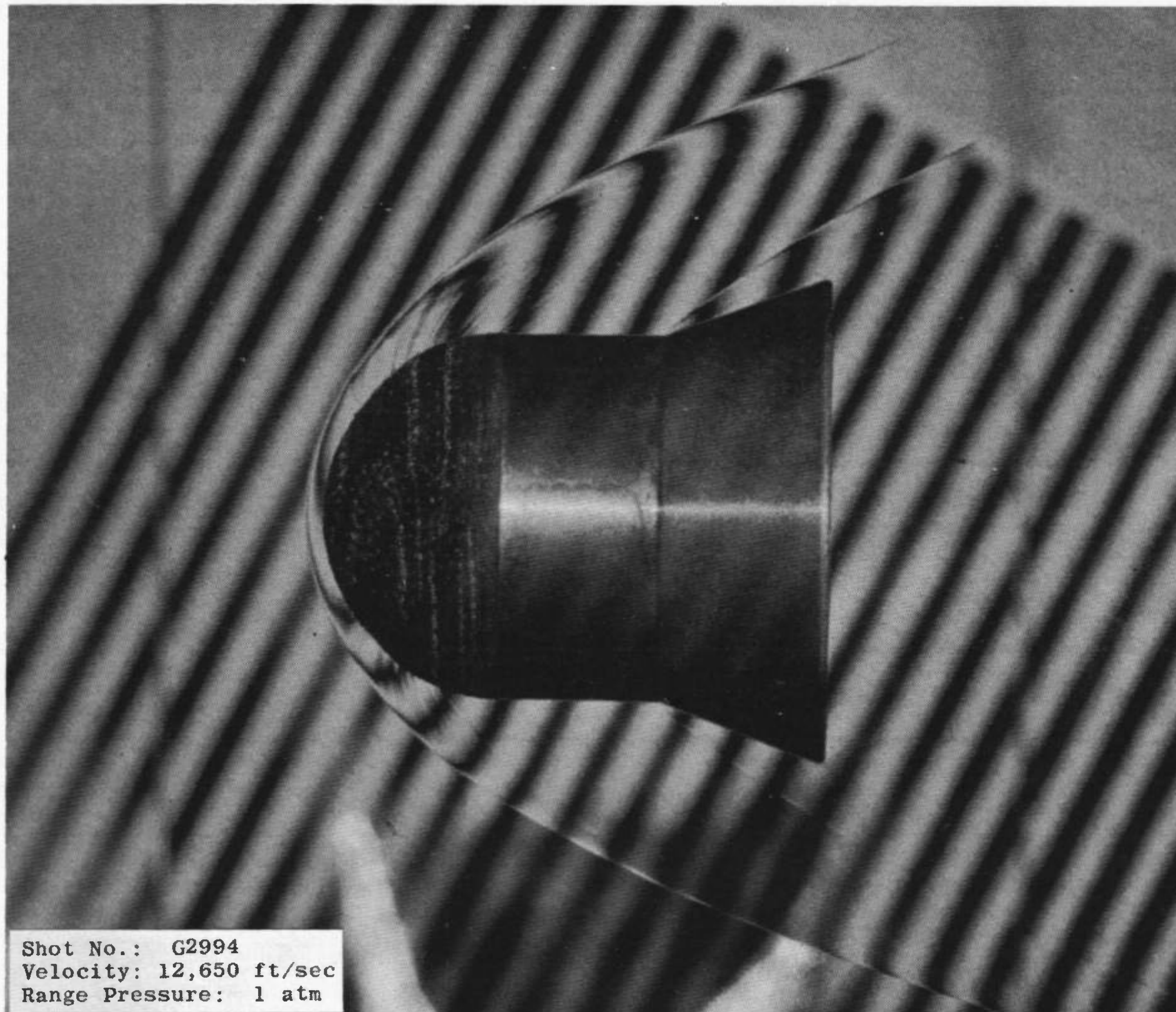
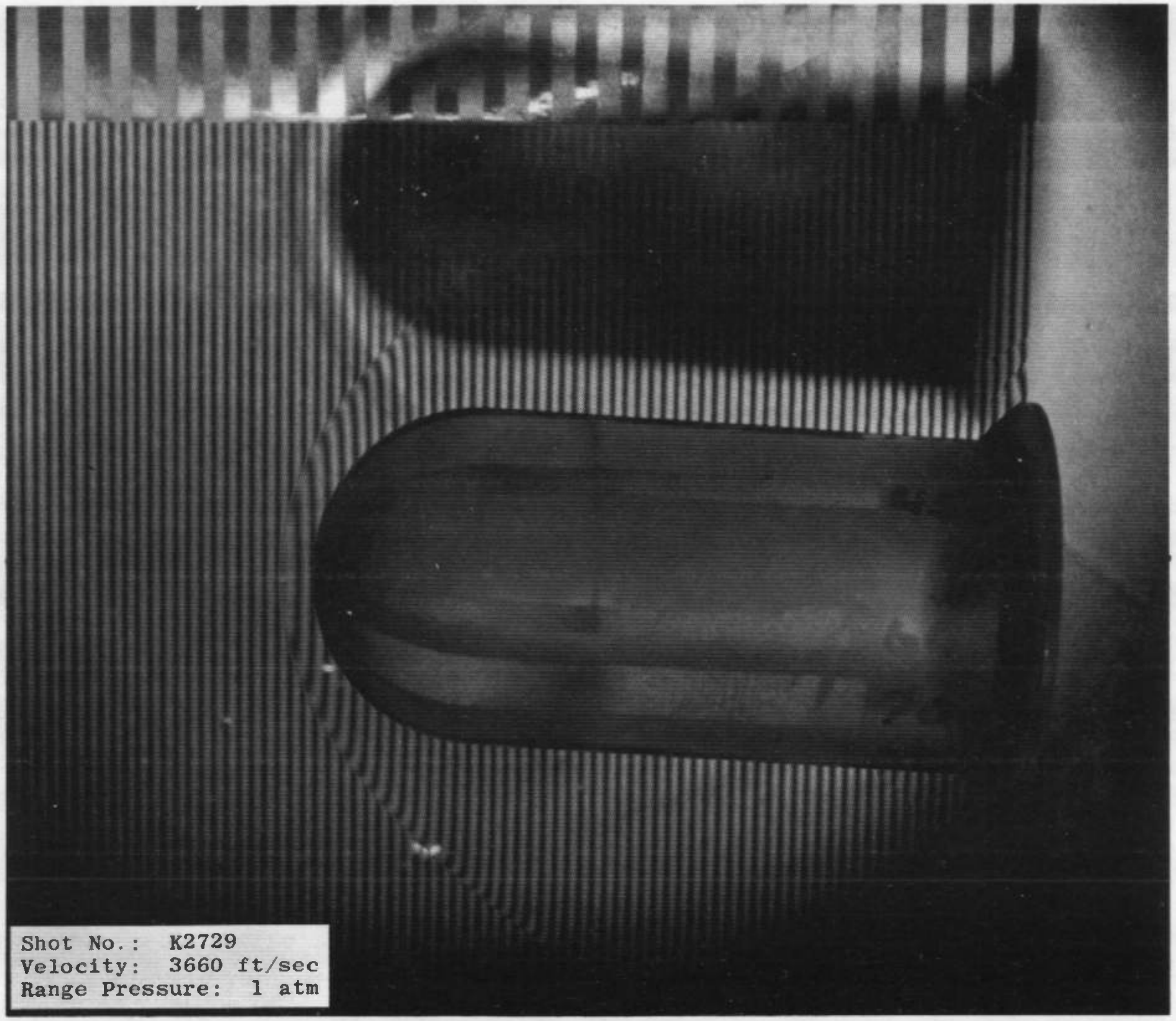


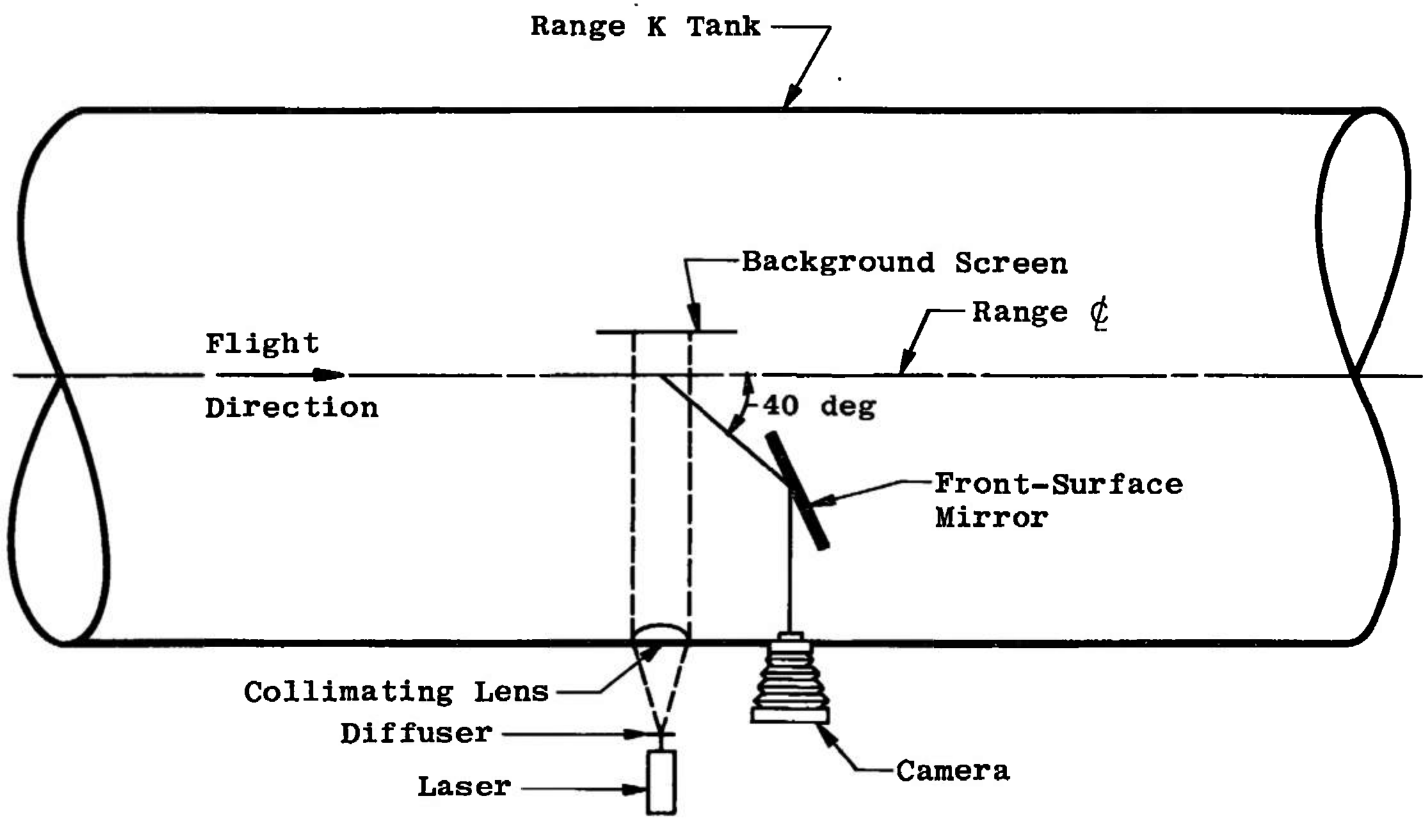
Fig. 7 Typical Aeroballistic Range Front-Light Photographic System



a. Photograph from Hyperballistic Range G
Fig. 8 Front-Light Laser Photographs Demonstrating Flow Visualization Capability



b. Photograph from Hyperballistic Range K
Fig. 8 Concluded



Note: Side view cameras (see Fig. 7) are not shown.

Fig. 9 Aeroballistic Range K Laser Photography Station with Oblique-View Camera

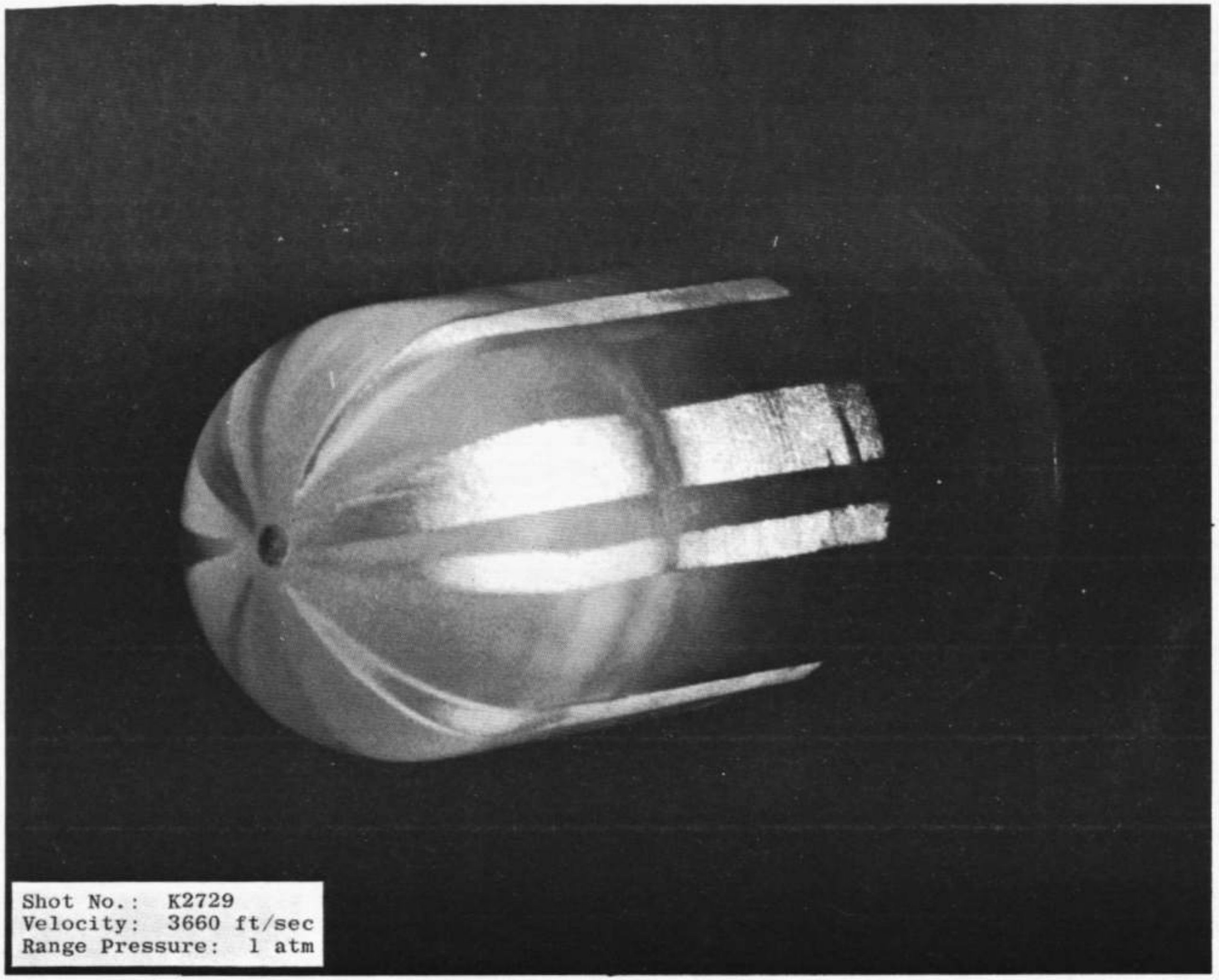


Fig. 10 Oblique-View Laser Photograph—Range K

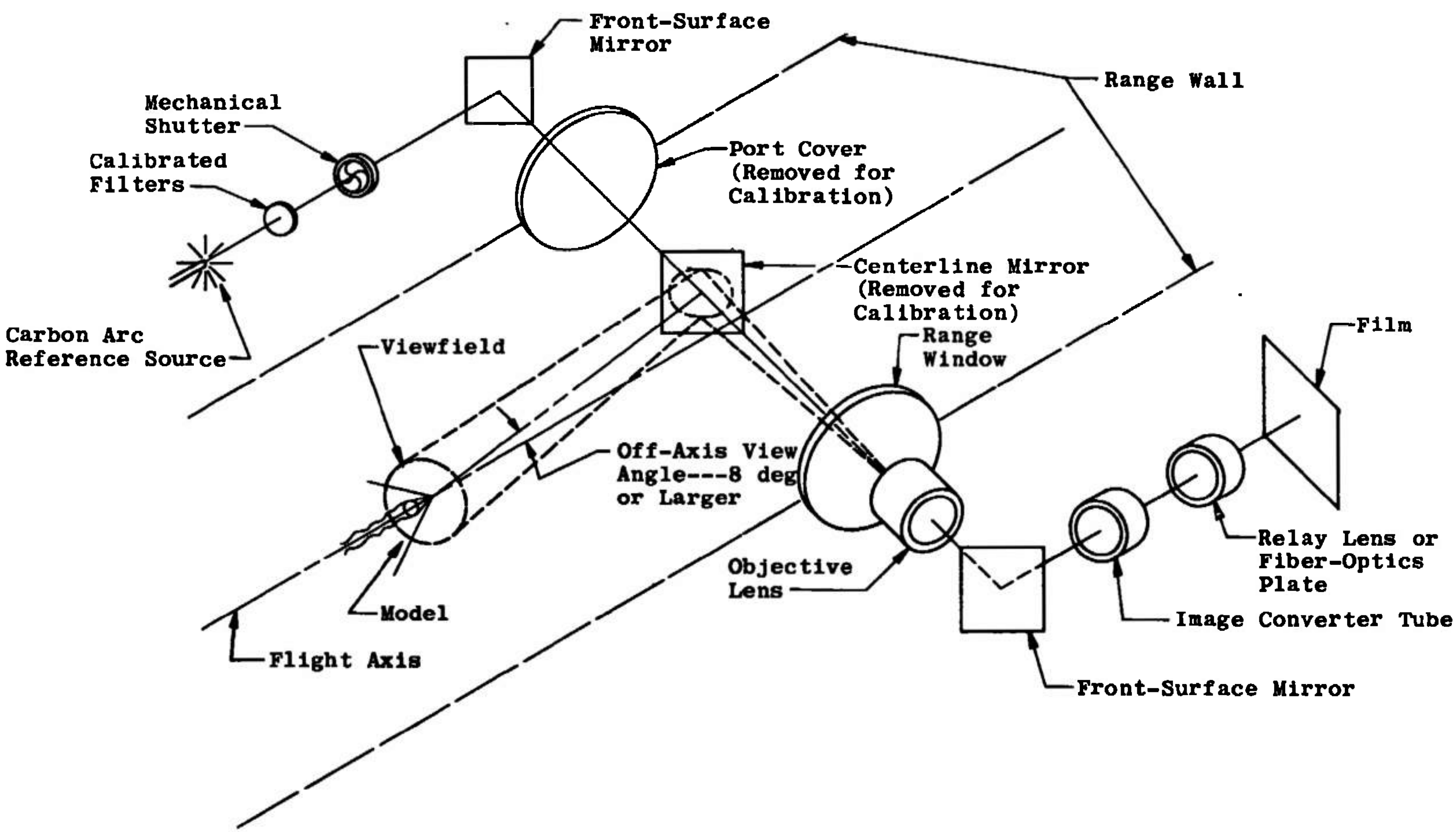
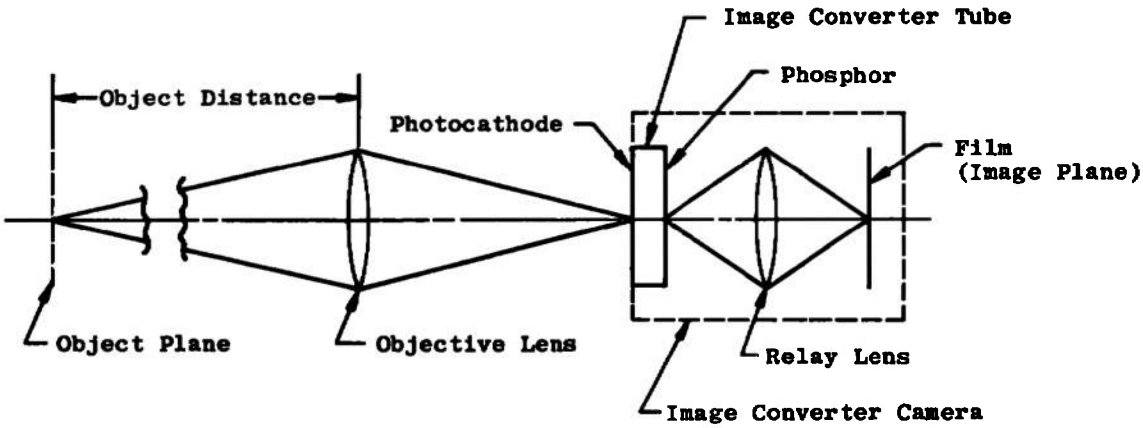
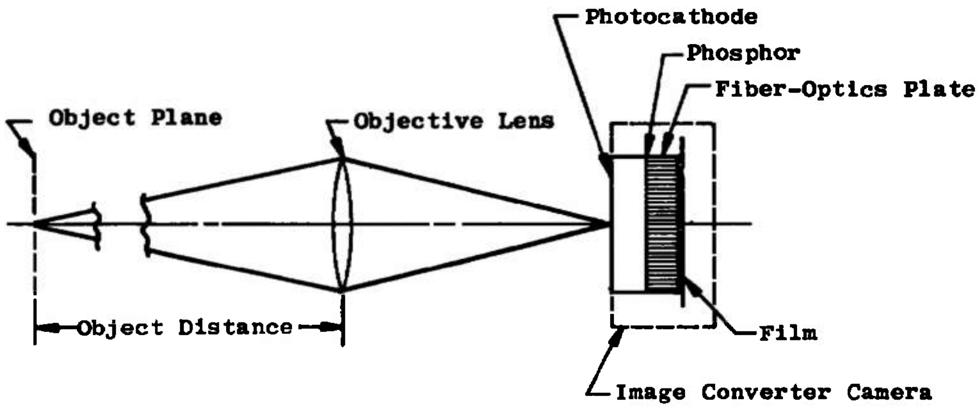


Fig. 11 Aeroballistic Range G Photographic Pyrometer System



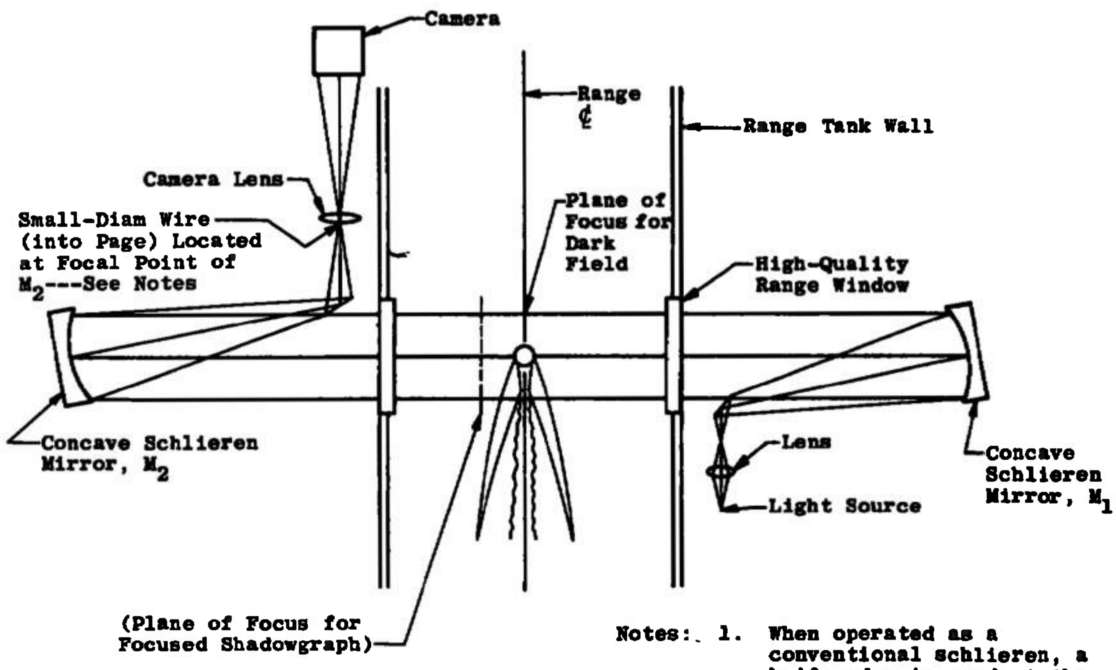
a. Relay-Lens Coupled



Note: Focal Lengths, Object Distances, and Other Characteristics Are Given in Table II

b. Fiber-Optics Coupled

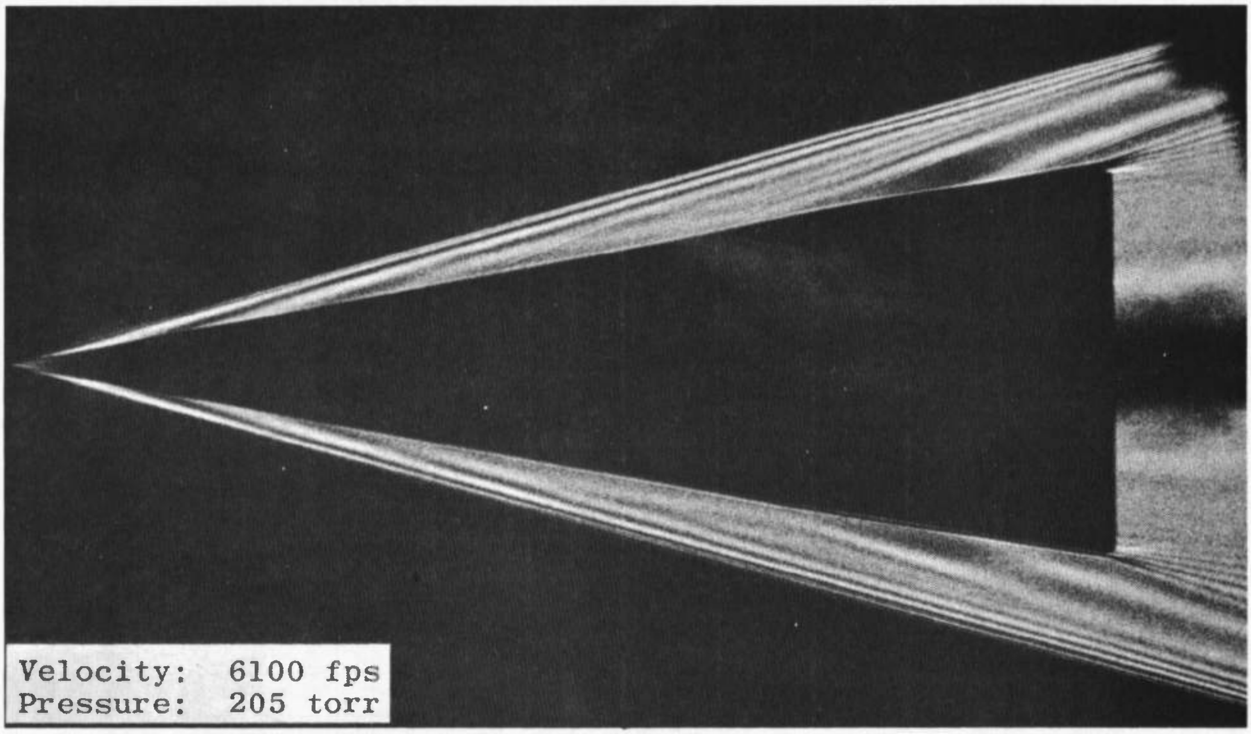
Fig. 12 Optical Diagrams for Image Converter Cameras—Range G Photopyrometer Systems



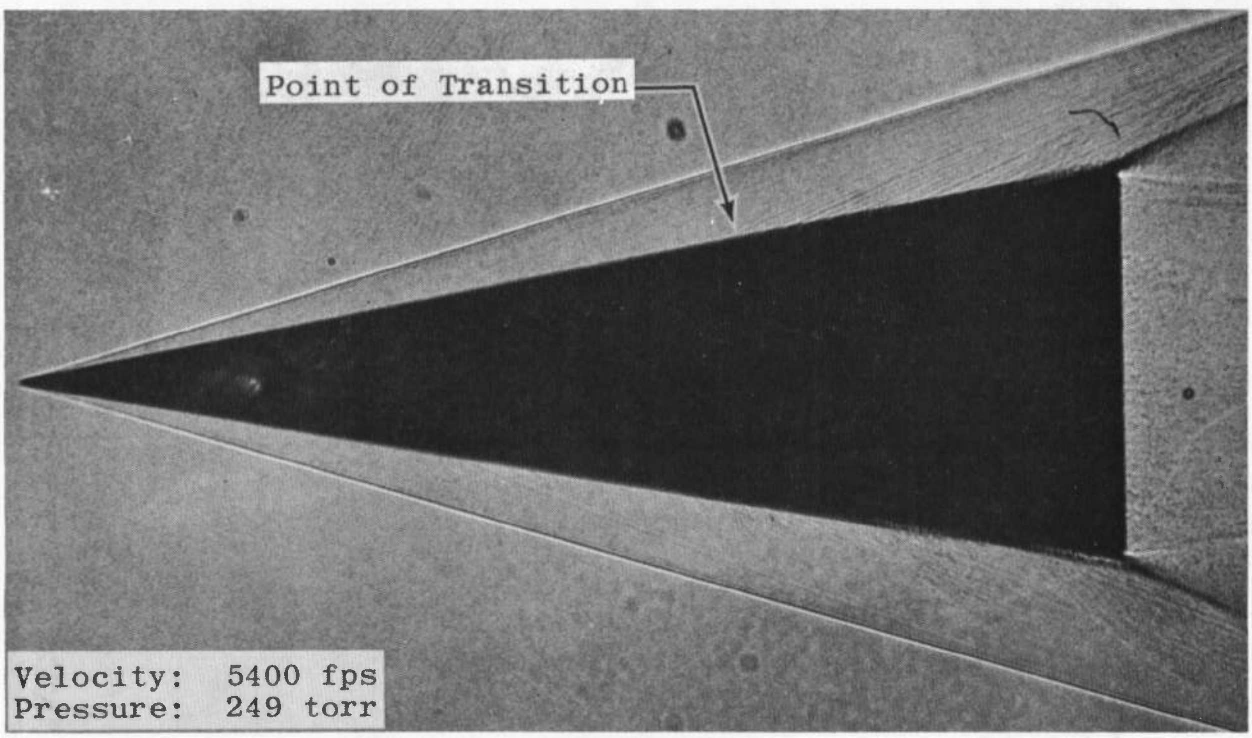
Notes:

1. When operated as a conventional schlieren, a knife edge is used at the focal point of M_2.
2. When operated as a focused shadowgraph, no obstruction is used at the focal point of M_2.

Fig. 13 Schlieren Configuration Used in Aeroballistic Ranges G and K—Dark-Field Arrangement



a. Dark-Field Schlieren



b. Focused Shadowgraph

Fig. 14 Results from Flow Visualization Techniques Evaluated for Boundary-Layer Transition Studies in Range K

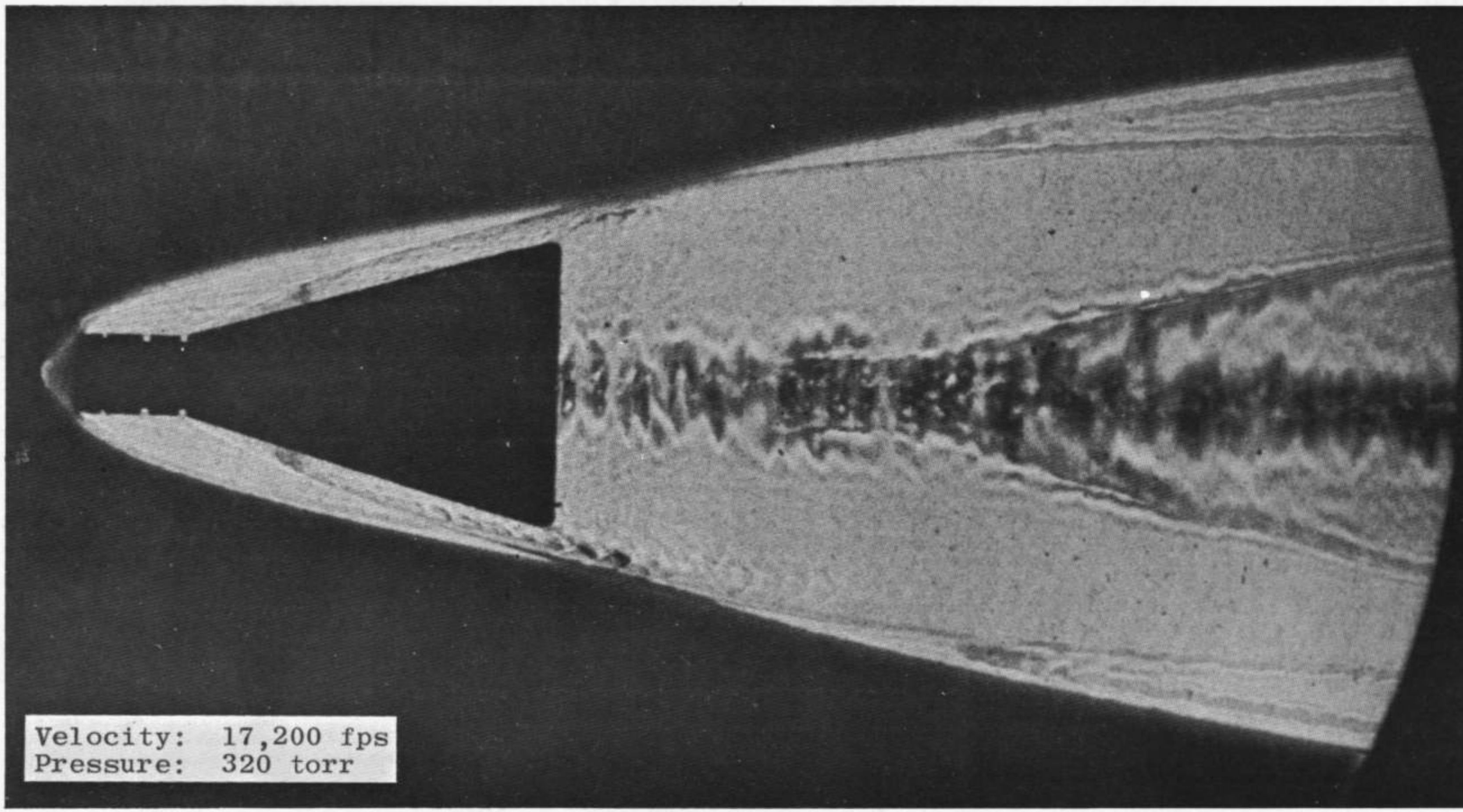


Fig. 15 Dark-Field Schlieren Result from Range G

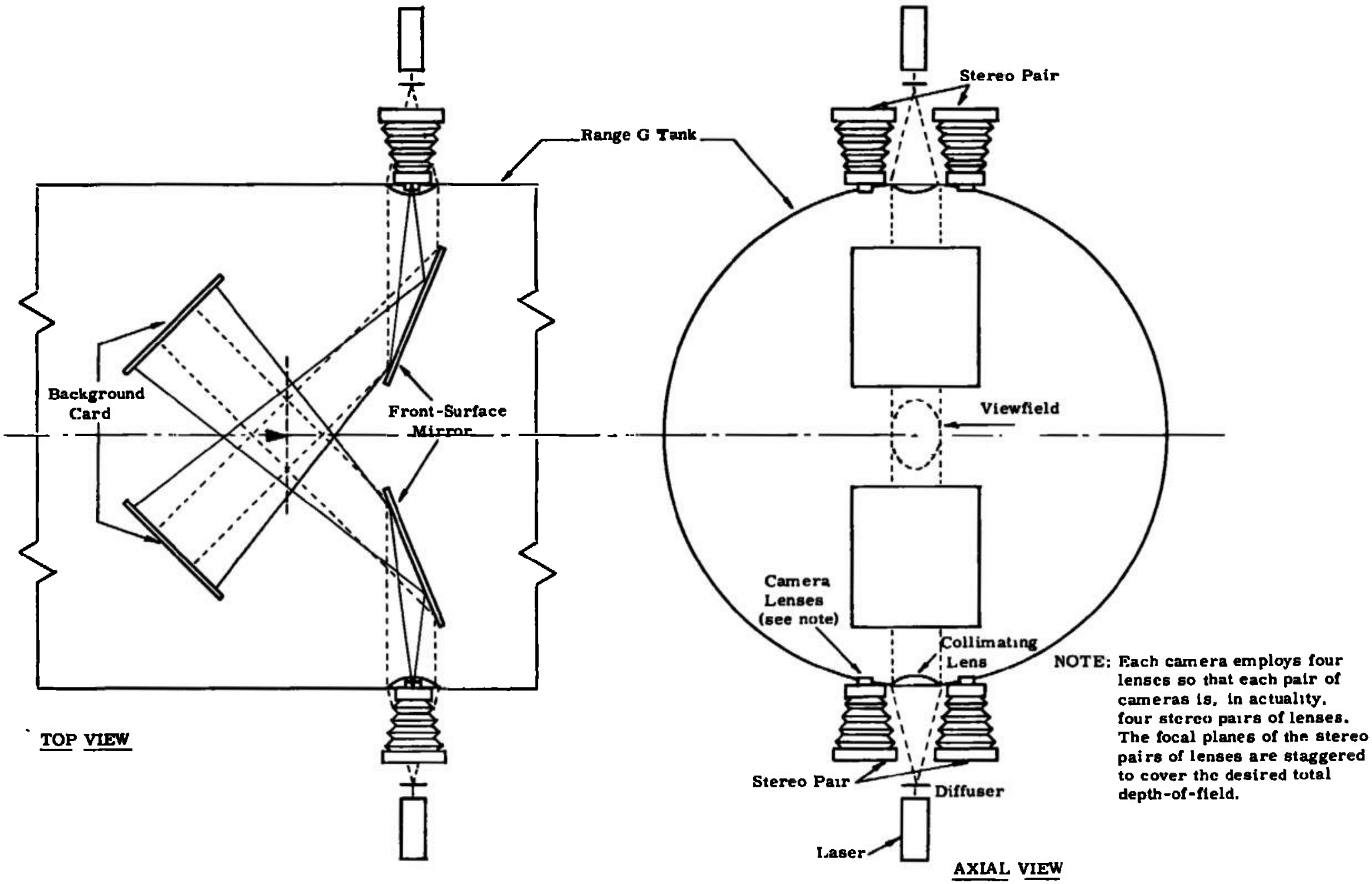
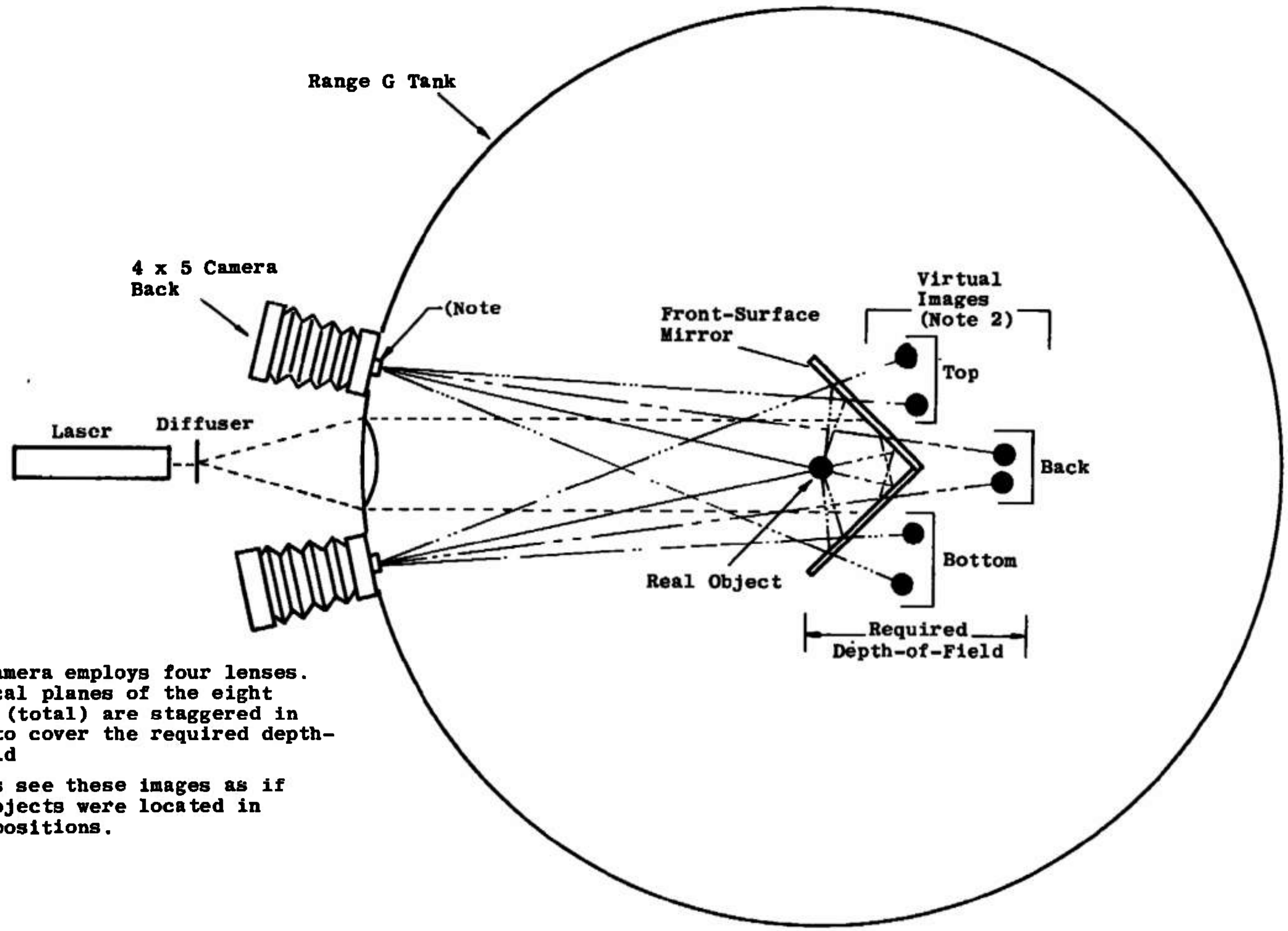


Fig. 16 Oblique (45 deg from Headon) Systems for Stereo Viewing of Entire Nose



Notes: 1. Each camera employs four lenses. The focal planes of the eight lenses (total) are staggered in order to cover the required depth-of-field

2. Cameras see these images as if real objects were located in these positions.

Fig. 17 Multiview Laser Photography Technique

TABLE I
AEROBALLISTIC RANGE G LASER PHOTOGRAPHY SYSTEMS

Location (distance from range entrance), ft	No. of Cameras	No. of Lenses	f-Number	Focal Length, in.	Total Photographic Viewfield Dimensions	Mode of Operation
57	2	2	22	19	12-in. diam by 16 in. deep	front-lighted
	1	4	16	5.5		
193	1	1	32	19	16-in. diam by 16 in. deep	front-lighted
	1	4	16	5.5		
313	2	8	16	5.5	15-in. diam by 32 in. deep	front-lighted
393	2	8	16	5.5	15-in. diam by 32 in. deep	front-lighted
513	4	15	16	5.5	23-in. diam by 26 in. deep	front-lighted
613	4	16	16	5.5	21-in. diam by 27 in. deep	front-lighted
733	6	24	16	5.5	39-in. diam by 38 in. deep	front/back lighted*
852	6	24	16	5.5	39-in. diam by 38 in. deep	front/back lighted*

* Depending on location of model in viewfield, usually front-lighted.

Note: The Range K system employs one camera with four 5.5-in. f.l. lenses (broadside view), one camera with one 19-in.-f.l. lens (also broadside view), and one oblique-view (40 deg from head-on) camera with one 19-in.-f.l. lens. This front-lighted system is located 26 ft from range entrance and views a region 10 in. in diameter by 16 in. deep.

TABLE II
CHARACTERISTICS OF IMPROVED RANGE G PHOTOGRAPHIC PYROMETRY SYSTEMS

Location (distance from range entrance), ft	System Description	I. C. Tube Resolution, mil	Objective Lens Focal Length, in.	Object Distance, in.	Objective* Lens Magnification	Viewing Angle (from head-on), deg	Viewfield Diameter, in.	Exposure Time, nsec	Object Plane Motion Blur,** mil	Object*** Plane Resolution, mil
210	2.5-in.-diam Abtronics I. C. camera with relay lens coupling to film	4	36	168	0.272	9	9.2	100	3	14.7
395	2.3-in.-diam Cordin I. C. camera with fiber optics coupling to film	3.3	24	168	0.167	9	13.8	10	0.3	19.8
593	5.0-in.-diam Abtronics I. C. camera with relay lens coupling to film	5	36	168	0.272	15	18.4	100	6	18.4

*Should not be confused with overall system magnification, does not include effect of relay lens

**Based on model velocity of 18,000 ft/sec, viewing angles and exposure times as listed.

***Two points on the object, separated by this distance, can be unambiguously resolved in the final image. Values calculated from I. C. tube resolutions and objective lens magnification, effects of objective lenses and relay lenses on resolution are negligible in comparison with the limits imposed by I. C. tubes.

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13. ABSTRACT Evaluations and remedial modifications to laser photography systems have resulted in a 30-percent increase in reliability for optimum performance. Another unique modification to the laser photographic technique has added the capability for flow visualization when desired. A 70-percent increase in spatial resolution has resulted from refinements to photopyrometry systems. Evaluations have shown that temperature measurement accuracies on the order of ±2 percent (±80°K at a measured temperature of 4000°K) may be achieved with the improved systems. Investigations of schlieren-related flow visualization techniques resulted in the selection of a focused shadowgraph arrangement for detection of boundary-layer transition on conical models. Preliminary designs for photographic instrumentation systems for use during erosion testing have been completed.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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evaluations						
revisions						
laser						
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1. Laser photography
2. Aerospace facilities -- Flow Visualization
2 " "

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